Tension Between A Fourth Generation And The LHC Higgs Searches

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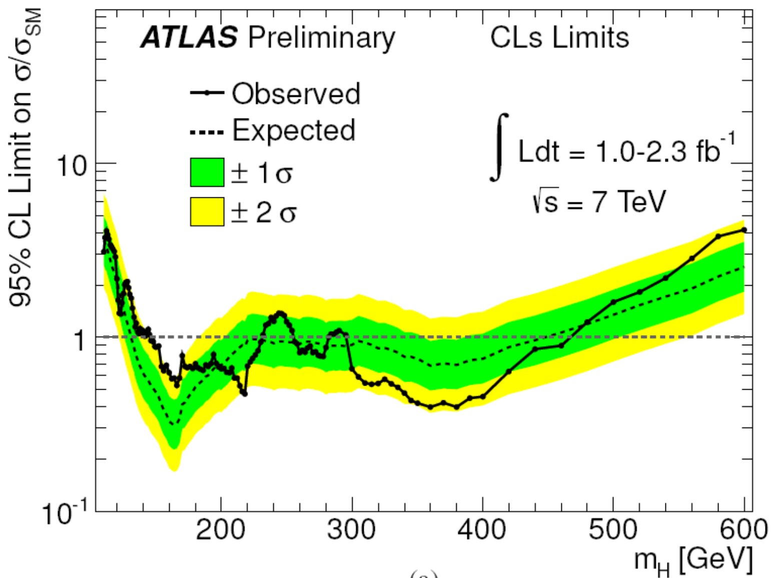
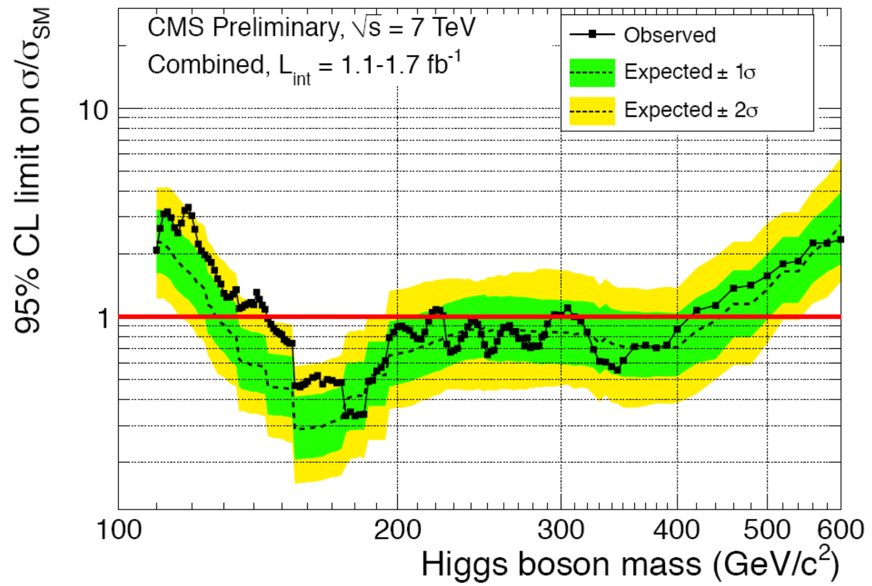
Xiao-Gang He and German Valencia, arXiv:1108.0222
Xiao-Gang He and Jusak Tandean, arXiv:1109.1277

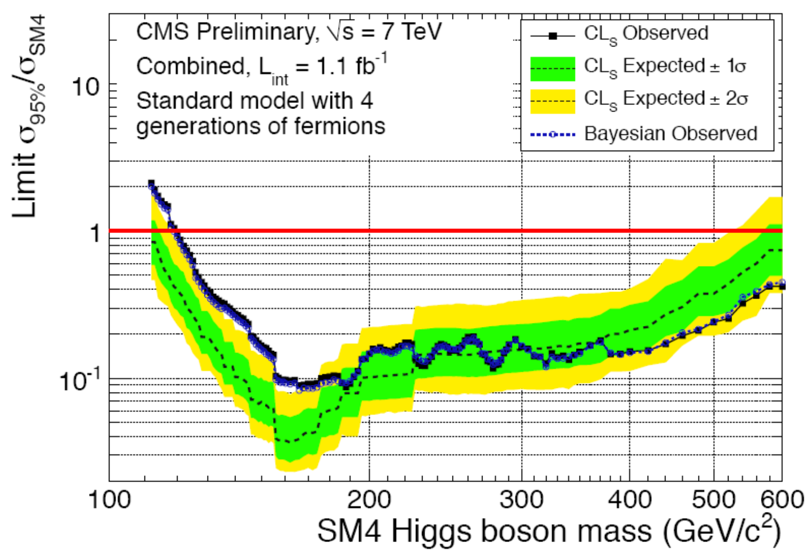
LHC Higgs searches

ATLAS and CMS have performed searches for Higgs at the LHC with null results.



(a)





For SM with 3 generations (SM3):

Higgs h with a mass in the ranges have been excluded at 95% c.l.

ATLAS: 146 – 232, 256 – 282, 296 – 466 GeV (1.0 to 2.3 fb^{-1})

CMS: 149 – 206, 300 - 440 GeV (1.0 fb^{-1})

wider range at 90% c.l.

For SM with 4 generations (SM4): at 95% c.l.

Mass between120 – 600 GeV excluded by both ATLAS and CMS

Main production and search modes:

g g -> h -> WW*, ZZ*, $\gamma\gamma$, τ anti-τ, b anti-b, ...

WW*, ZZ* become dominant modes if h mass larger than 140 GeV.

m_h smaller than 120 GeV small visible width, harder to detect.

g g -> h loop induced process in SM

σ_{SM}: ~ N^2 (N: number of heavy quarks in the loop)

SM3: one heavy quark, the top t: N= 1; SM4: t, t' and b': N = 3

$\sigma_{SM4}/\sigma_{SM3}$ ~ 9 (the reason why a wider range for SM4 has been excluded compared with SM3)

LHC may well discover the SM Higgs in the electroweak precision data preferred region ~ 120 GeV, or some where below 1 TeV but with SM3 or SM4 cross section?

If with SM3 like cross section, 4^{th} generation is ruled out?

If LHC will not find the Higgs in the whole expected mass range up to TeV, an elementary Higgs may not exist? Also SM4 is not favored.

A tension between a 4^{th} generation and LHC Higgs search data?!

Direct search for the 4th generation:

$M_4 > 335$ GeV, Tevatron;

$M_{t'} > 270$ GeV, $M_{b'} > 290$ GeV at 95%c.l.(ATLAS),

$M_{t'} > 450$ GeV, $M_{b'} > 495$ GeV at 95% c.l. (CMS)

More search at the LHC needed.

Too heavy a 4th generation (> 600 GeV or higher), strongly interacting due to large Yukawa couplings. Hard to distinguish resonant peak of the heavy 4th generation quark.

Is it possible to evade the Higgs search bounds to leave more room for the 4th generation?

Yes, if there are new physics beyond SM to modify

1. gg -> h production
2. h -> WW*, ZZ* decay modes
3. h decays with a large invisible branching ratio

…

New Physics Modifying Higgs Production

If there is new physics which contributes significantly to gg -> h and cancels the SM3(SM4) contribution, the production of h can be reduce which leads to event number reduction.

This can get SM4 to mimic SM3, and to recover the excluded Higgs mass regions. Or make the SM3 production cross section smaller, recover some Higgs mass exclusion region.

Example: Color octet Higgs doublet S = (8,2,1/2). (Manohar&Wise)

Being colored particle, may contribute to g g-> h.

Colored S does not mixing with h, h decay modes not modified.

λ_1 and λ_2 terms induce hSS coupling , S in loop induces gg -> h

$$\begin{aligned} V \;=\; & \frac{\lambda}{4}\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_S^2 \mathrm{Tr} S^{\dagger i} S_i + \lambda_1 H^{\dagger i} H_i \mathrm{Tr} S^{\dagger j} S_j + \lambda_2 H^{\dagger i} H_j \mathrm{Tr} S^{\dagger j} S_i \\ + \; & \left[\lambda_3 H^{\dagger i} H^{\dagger j} \mathrm{Tr} S_i S_j + \lambda_4 H^{\dagger i} \mathrm{Tr} S^{\dagger j} S_j S_i + \lambda_5 H^{\dagger i} \mathrm{Tr} S^{\dagger j} S_i S_j + \text{ H.c}\right] \\ + \; & \lambda_6 \mathrm{Tr} S^{\dagger i} S_i S^{\dagger j} S_j + \lambda_7 \mathrm{Tr} S^{\dagger i} S_j S^{\dagger j} S_i + \lambda_8 \mathrm{Tr} S^{\dagger i} S_i \mathrm{Tr} S^{\dagger j} S_j \\ + \; & \lambda_9 \mathrm{Tr} S^{\dagger i} S_j \mathrm{Tr} S^{\dagger j} S_i + \lambda_{10} \mathrm{Tr} S_i S_j S^{\dagger i} S^{\dagger j} + \lambda_{11} \mathrm{Tr} S_i S_j S^{\dagger j} S^{\dagger i} \; . \end{aligned}$$

$$\mathcal{L} = (\sqrt{2} G_F)^{1/2} \frac{\alpha_s}{12\pi} \, G^A_{\mu\nu} G^{A\mu\nu} h \left(n_{hf} + \frac{v^2}{m_S^2} \frac{3}{8} (2\lambda_1 + \lambda_2)\right)$$

The contribution from λ_2 to the electroweak parameter S

$$\lambda_2 \;=\; 6\pi \frac{m_S^2}{v^2} S \qquad \text{for } M_h \;=\; 300 \text{ GeV is, } S \;=\; -0.07 \pm 0.09$$

Saturate S by color octet, enough to suppress SM3 by 1σ level.

Taking $\lambda_1 = -8$, can half the SM4 production cross section and therefore recover LHC excluded regions.

New Physics Modifying h -> WW* & ZZ*

Example: A two Higgs doublet model:

(Das&Kao;Bar-Shalom,Nandi&Soni…)

In a generic two Higgs doublet model with scalar fields H_1 and H_2 each has a vev v_1, v_2. H_1 couples to the first three generations and H_2 couples to the fourth generation,

Yukawa couplings are given by

$$\begin{aligned}\mathcal{L} \;=\; & -\bar{Q}^i_L Y^u_{ij} \tilde{H}_1 U^j_R - \bar{Q}^i_L Y^d_{ij} H_1 U^j_R - \bar{L}^i_L Y^e_{ij} H_1 E^j_R + \text{ H.c.} \\ & -\bar{Q}^4_L Y^u_{44} \tilde{H}_2 U^4_R - \bar{Q}^4_L Y^d_{44} H_2 U^4_R - \bar{L}^4_L Y^e_{44} H_2 E^4_R + \text{ H.c.}\end{aligned}$$

In general, the Higgs potential parameters mix the neutral real components of the doublets $h^0_{1,2}$ to form the physical neutral scalars h and H

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

The couplings of h and H to W and Z bosons are given by

$$\mathcal{L} = \left(2\frac{m_W^2}{v}W^{+\mu}W_\mu^- + \frac{m_W^2}{v}Z^\mu Z_\mu\right)(H\sin(\beta-\alpha) + h\cos(\beta-\alpha)) \ ,$$

where β is defined by $\tan^{-1}(v_2/v_1)$ and $v^2 = v_1^2 + v_2^2$, and $\tan\beta$

The Yukawa couplings of h and H are given by $(i = 1, 2, 3)$

$$\begin{aligned}\mathcal{L} \ = \ & -\frac{1}{v}(\bar{u}^i m_i^u u^i + \bar{d}^i m_i^d d^i + \bar{e}^i m_i^e e^i)\left(\frac{\cos\alpha}{\cos\beta}h - \frac{\sin\alpha}{\cos\beta}H\right) \\ & -\frac{1}{v}(\bar{u}^4 m_4^u u^4 + \bar{d}^4 m_4^d d^4 + \bar{e}^4 m_4^e e^4)\left(\frac{\sin\alpha}{\sin\beta}h + \frac{\cos\alpha}{\sin\beta}H\right) \ .\end{aligned}$$

With a 4th generation

$$\frac{\sigma_h}{\sigma_{SM}} \equiv \frac{\sigma(pp\to h\to VV)}{\sigma(pp\to H_{SM}\to VV)} \ \sim \ \left[\left(2\frac{\sin\alpha}{\sin\beta} + \frac{\cos\alpha}{\cos\beta}\right)\cos(\beta-\alpha)\right]^2$$

$$\frac{\sigma_H}{\sigma_{SM}} \equiv \frac{\sigma(pp\to H\to VV)}{\sigma(pp\to H_{SM}\to VV)} \ \sim \ \left[\left(2\frac{\cos\alpha}{\sin\beta} - \frac{\sin\alpha}{\cos\beta}\right)\sin(\beta-\alpha)\right]^2$$

where $V = W$ or Z.

If h is the SM-like Higgs with coupling to W-pairs the same as that in the SM: $\beta = \alpha$,

h couplings to the fermions are also the same as those for the SM4 and $\sigma_h/\sigma_{SM4} \sim 1$.

If h is also the lightest scalar, this model has the same tension as described for SM4.

In this model, h can be the heavier neutral scalar and have a mass outside the range of current searches.

But H is actually the lighter scalar which can be produced at the LHC, the search requires a different strategy as it does not couple to W-pairs, $\sigma_H/\sigma_{SM} << 1$.

If one chooses H to have SM-like couplings to W-pairs, the roles of h and H are switched.

It is not possible to find values of α and β that simultaneously suppress σ_H/σ_{SM} and σ_h/σ_{SM}.

Invisible Higgs Decays and Light Dark Matter

If there is a new invisible width Γ_{inv} beside SM decay width Γ_{SM},
One can define: $R = \Gamma_{SM}/(\Gamma_{SM}+ \Gamma_{inv})$

If visible decay width, and gg -> h are not changed,
then the LHC measured number of event N_{SM} for SM
and $N_{(SM+inv)}$ for the new model is related by: $N_{(SM+inv)} = R\, N_{SM}$

This leads to a weakening of the exclusion ranges.

For example, for R ~ 1/9, in this new model the event number of SM4 is actually the same as the real SM3, the exclusion region would not be 120 – 600 GeV but similar to the SM3.

R can also, of course, recover the excluded region for SM3.

The Darkon Model SM+D as a realistic realization

SM+D: SM3(SM4) + a real SM singlet D darkon field (plays the role of dark matter).
(Sileira&Zee, McDonald)

Beyond the SM part, the Lagrangian of the model

$$\mathcal{L}_D = \frac{1}{2}\partial^\mu D\, \partial_\mu D - \frac{1}{4}\lambda_D D^4 - \frac{1}{2}m_0^2 D^2 - \lambda D^2 H^\dagger H \ ,$$

where λ_D, m_0, and λ are free parameters and H is the Higgs doublet containing the physical Higgs field h

Only two of its free parameters besides m_h are :
λ and the darkon mass $m_D = (m_0^2 + \lambda v^2)^{1/2}$

D is stable due to a D-> - D Z2 symmetry.

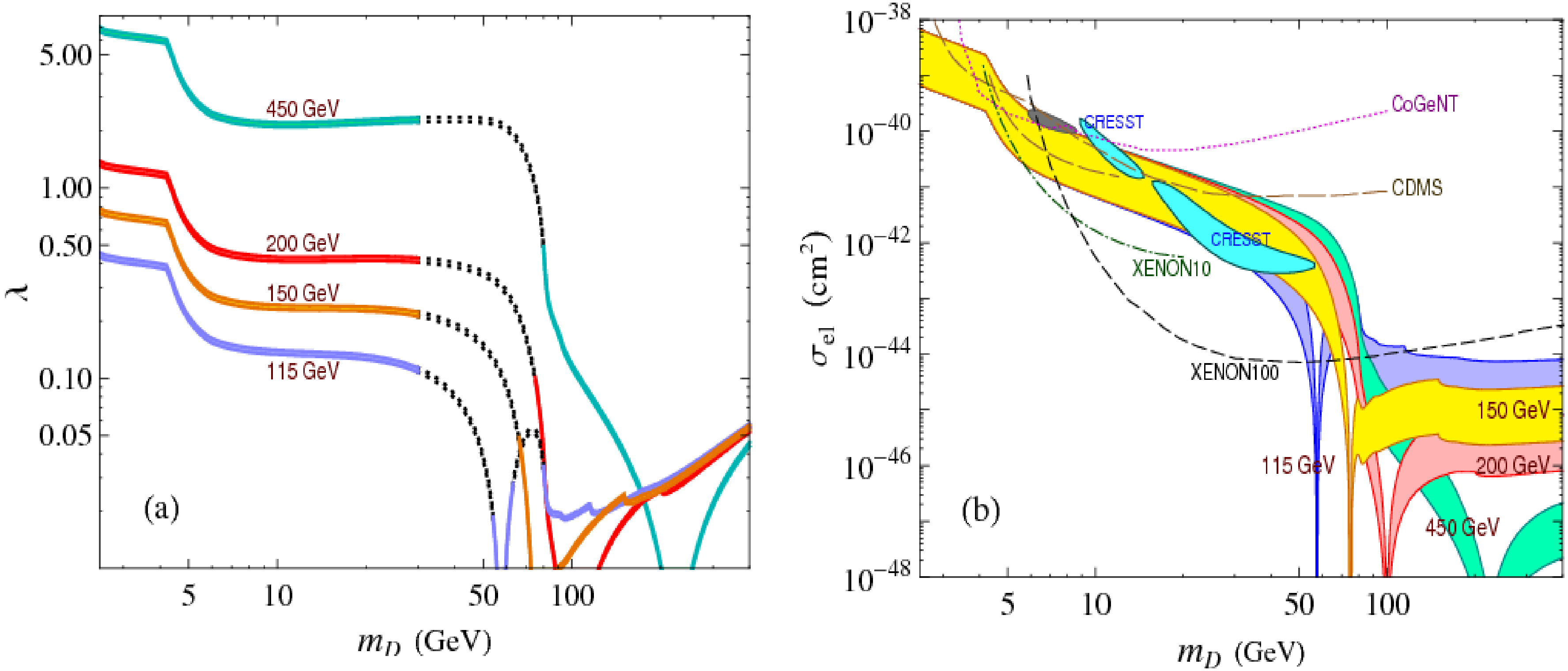
After H develops VEV, there is a term: λ v DD h.

This term is important for annihilation of D D -> h -> SM particle

This term also induce h -> DD if DM mass is less than half of the Higgs mass

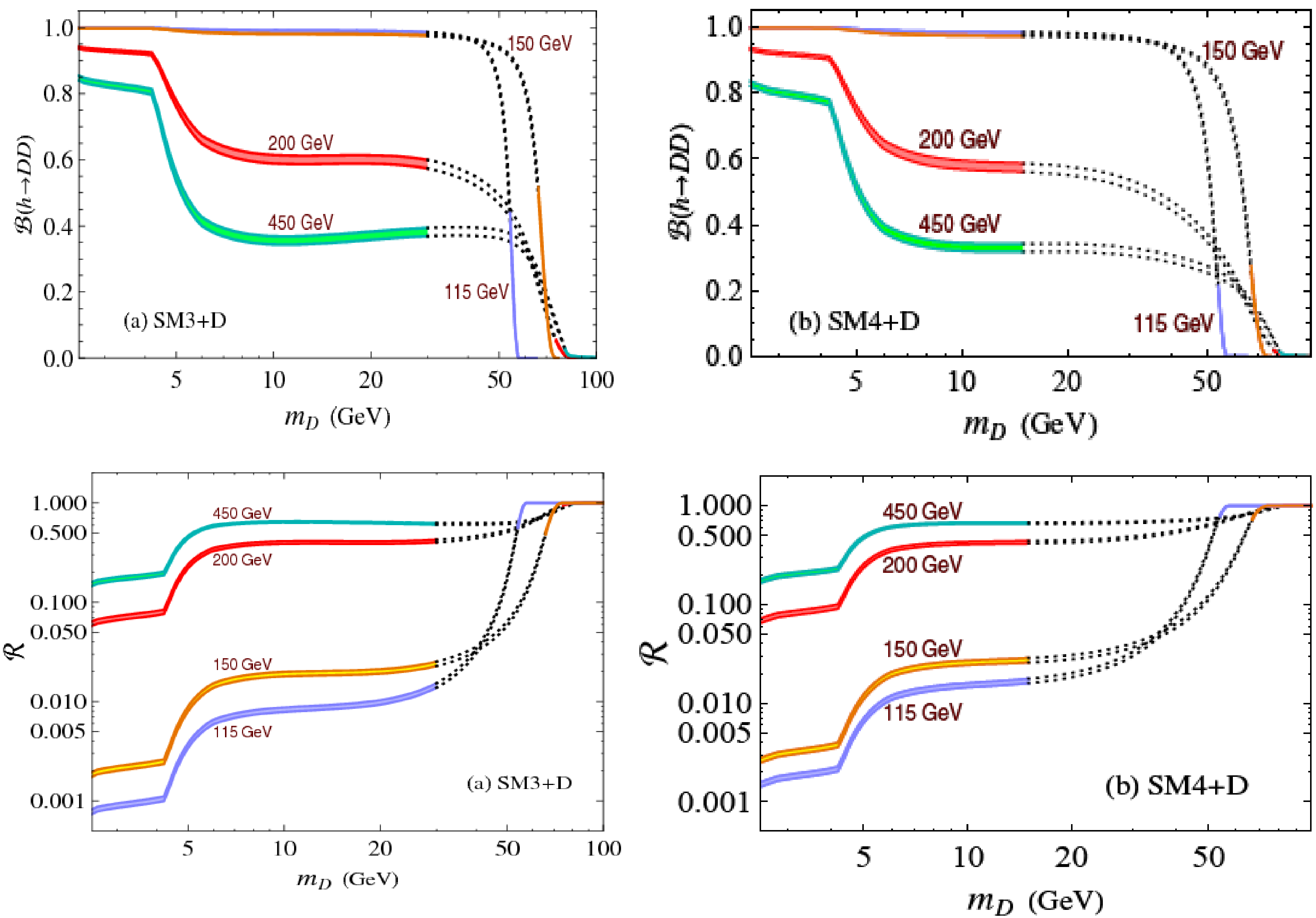
increasing the invisible decay width and make the LHC detection harder!

Visible decay modes and gg -> h are the same as SM3 (SM4)



Left: constraint from relic density $\Omega_D h^2 = 0.1123 \pm 0.0035$

Right: constraints from various direct DM detection.



1.0
0.8
0.6
0.4
0.2
0.0
$\mathcal{B}(h\to DD)$
150 GeV
200 GeV
450 GeV
115 GeV
(a) SM3+D
5
10
20
50
100
m_D (GeV)
(b) SM4+D
1.000
0.500
0.100
0.050
0.010
0.005
0.001
$\mathcal{R}$

TABLE I: Ranges of reduction factor $\mathcal{R}$ corresponding to the allowed m_D regions (I) from 2.5 to 15 GeV and (II) not far from, but less than, $m_h/2$ in (a) SM3+D and (b) SM4+D for $m_h = 115, 150, 200, 450$ GeV.

	115	150	200	450
I a	[0.0007,0.009]	[0.0018,0.020]	[0.058,0.41]	[0.15,0.65]
II a	[0.56,1]	[0.48,1]	[0.95,1]	[0.97,1]
I b	[0.0014,0.018]	[0.0025,0.029]	[0.065,0.44]	[0.16,0.68]
II b	[0.79,1]	[0.72,1]	[0.98,1]	[0.99,1]

Most ranges of Higgs mass excluded for SM3 at LHC can be recovered by SM+D

In the low DM mass (half of Higgs mass) ranges excluded for SM4 can be recovered (some regions can be recovered).

Increased luminosity at the LHC may well discover a SM-like Higgs in the currently excluded Higgs mass ranges. Also the 4th generation can exist.

Future DM direct search can also provide further information about Higgs mass.

There may be a deep connection between dark matter, flavor and Higgs physics.